Temanejo- a debugger for task based parallel programming models

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Abstract. We present the program Temanejo, a debugger for task based parallelisation models such as StarSs. The challenge in debugging StarSs applications lies in the fact that tasks are scheduled at runtime, i.e dynamically in accordance to the data dependencies between them. Our tool assists the programmer in the debugging process by visualising the task dependency graph and allowing to control the scheduling of tasks.

The toolset consists of the library AYUDAME which communicates with the StarSs runtime on one side and of the debugger Temanejo on the other side which communicates with AYUDAME. Temanejo provides a graphical user interface with which the application can be analysed and controlled.

Keywords. Debugging, HPC, task parallelisation, StarSs, Temanejo

Introduction

Task based programming models have amplified the landscape of parallelisation paradigms. In these models, parallelism is not dictated on the level of operations. The programmer rather indicates data dependencies between parts of the code which become *tasks* and then are scheduled by an execution framework at runtime. This way the program can "react" on internal irregularities, e.g. differences in execution time of each task, and external conditions, such as hybrid architectures.

One family of these programming models are the StarSs models [1,2]. The "Ss" stands for *superscalar* and indicates that these models aim at scaling on modern supercomputers consisting of millions of processing units. The "Star" in the name paraphrases a wildcard which stands for the different implementations of this model like *CellSs*, *GPUSs*, *GridSs*, *OMPSs* and *SMPSs* [2] among others. They differ in the supported programming languages, whether functions (respectively subroutines) or other blocks of code are parallelised and whether the target platform is, for instance, a grid or a node of CPUs or GPUs.

Debugging a task parallel program differs from debugging an otherwise parallelised program as the parallelisation is determined by data dependencies instead of explicit scheduling of tasks and synchronisation between them. Therefore, the development of new debugging tools capable of assisting the programmer with

debugging task parallel programs is a crucial condition for effectively exploiting the possibilities of these models.

We present a debugging toolset for task parallel programs consisting of two components: a library called AYUDAME¹, acting as a thin communication layer and enabling the debugger to receive information about the program and send commands back to it, and the actual debugger TEMANEJO² which enables the user to view the extracted information and issue commands via a highly interactive graphical user interface.

For this work, we used the StarSs implementations SMPSs and OMPSs. Nevertheless, the basic concepts of how to debug a task parallel program are the same regardless of the specific framework.

In section 1, we elaborate on the idea and further implications of task based parallelism. We present different strategies and actions a debugger should provide and discuss how these features were implemented in the presented debugger Temanejo in section 2. Finally, we summarise the results and give an outlook on future enhancements to the debugger in section 3.

1. Task based parallelism

In contrast to other task based parallel programming models, the focus in the StarSs family lies on the data dependencies between parts of the program which are defined as tasks. In SMPSs, for example, the programmer marks functions or subroutines as "potentially parallel" using a special #pragma syntax. A typical function declaration in C looks like this:

```
#pragma css task input(a) inout(b) output(c)
void func(int a, int *b, double *c)
{
    /* function body */
}
```

css³ is the identifier of the pragma, the keyword task tells the precompiler that the following function declaration is to be treated as an SMPSs task, and the keywords input, inout and output specify the data dependencies for this task.

These pragmas are read by a compiler wrapper (smpss-cc) which embeds the program code into a runtime framework. This framework will initialise a previously defined number of threads and start the application. One of the threads will be the *master thread* which creates all tasks and takes care of proper initialisation and finalisation of the program. Moreover the master thread will execute all code outside of tasks. The tasks will be executed by the other threads, called *worker threads*

During runtime the SMPSs framework will assign all calls to functions marked by pragmas to a thread for execution depending on the specified dependencies.

¹Spanish for help me

²Spanish for *I handle you*

³css stands for cell super scalar and is a historical remnant of the first versions of SMPSs.

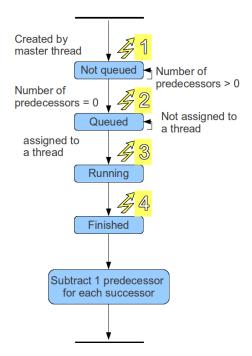


Figure 1. State transition diagram of a task. The task is always in one of the states "not queued", "queued", "running" or "finished". The processing of the successors is not counted as an own state. The transition to a state is triggering an event indicated by the numbers.

To achieve this, a task must be in one of four states (see figure 1): "not queued", "queued", "running" or "finished". When tasks are created they are not queued in case they have pending dependencies, i.e., they read (input) from a memory address which has been declared output (or inout) by another task at an earlier time. Otherwise, the task is queued directly after creation.

When all tasks on which a task depends on are finished, the task is queued. A queued task can be run at any time by an idling thread. When a task is executed by a thread, its state changes to *running*. After finishing the taks, its state is *finished*.

The transition between the states is a useful information for the programmer (see section 2.2). Furthermore, the state transition diagram (figure 1) indicates that there is more than one way to block or prioritise a task. In the case of blocking, one can avoid for a task to be queued or avoid that it is ever dequeued for execution by a thread. While a task is blocked, one can let the other threads continue executing tasks or interrupt the program execution entirely. Other possibilities for debugging include stopping only a certain function or adding artificial dependencies in order to force a certain order of subtree execution.

Some of these possibilities are exploited by the debugger Temanejo. How this was done is explained in the following. An outlook on future features is given in section 3.

2. The debugger Temanejo

In this section we will investigate the different requirements regarding a debugging tool for task based problems and how the debugger Temanejo fulfils them. A rather technical introduction to Temanejo is given in the next section.

For the programmer it is necessary to see (section 2.2) and be able to manipulate (sections 2.3.1, 2.3.2 and 2.3.3) the dependencies which lead to the conditions for executing tasks and thus alter the way the runtime will step through the tasks. As an additional information the duration of each task can be displayed (section 2.4).

In contrast to other parallelisation strategies, when using task based models the programmer needn't (and cannot) know a priori when a certain task is executed. At compile time only the conditions for running a task are known. Therefore, classical debuggers which step through lines of code sequentially are not well suited for debugging task parallel programs. They form a part of the debugging process (see section 2.3.4) but need to be complemented by other tools.

2.1. Technical details

TEMANEJO is written in python and requires python version 2.6 or newer. Furthermore, it imports several modules, the most important being Networkx [3] for the graph data structure and pygtk [4] for the visualisation and the graphical user interface.

The debugger Temanejo is tightly linked to the small library Ayudame. This library serves as a thin communication layer between the runtime and Temanejo and has to be preloaded to the application. The SMPSs and OMPSs framework (thus indirectly the application) are instrumented with calls to an event handler which passes the information to the debugger as a set of 8 integer values containing an event id, the task id and, depending on the event, one or more of the following: the task id of a dependency, the memory address of a dependency, the id of the function assigned to the task, a thread id and/or a timestamp. This is done at certain crucial points in the program execution, for instance initialisation, task generation, task execution etc., the event function is called and will react accordingly. In most cases, it will simply pass the data (task id, thread id, dependencies and so forth) to the attached socket client (in this case Temanejo).

Temanejo uses this information to build an internal data structure representing the dependency graph. Each task is a node of this graph and each dependency an edge. Nodes and edges have properties such as the task status and the memory address of the dependency, respectively.

The information is displayed by Temanejo at the time it is received and the user can access the debugging features instantly by pressing buttons or right-clicking on nodes. There are four distinct properties available for displaying information: the node colour, the node-margin colour, the node shape and the edge colour. This way one can produce different representations of the same graph depending on what information is selected for visualisation at a given debugging session.

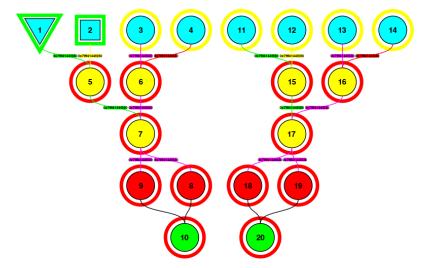


Figure 2. A simple dependency graph with two independent subtrees consisting of ten tasks each visualised by Temanejo. Eight independent tasks are drawn in blue, two of them scheduled (green margin) and six of them queued (yellow margin). Three tasks with input and output dependencies are shown in yellow, four reduction tasks in red and two tasks with only one input dependency in green. The red margin indicates that a task has unfulfilled dependencies and can therefore not be queued yet. The node shapes (triangle and box) denote two different worker threads, the circle shape indicates that the task has not been assigned to a thread yet. The text labels and colours of the edges indicate the memory addresses of the dependencies.

In the current version (0.5) Temanejo relies on connecting to the Ayudame library as a socket client when starting up. This means that either the parallel application has to run when Temanejo is started or Temanejo will start the application at the beginning of the debugging session.

2.2. Visualisation of the dependency graph

The first step of data-flow oriented debugging is to visualise the dependency graph. Often this already helps the programmer to spot errors or other short-comings of his program. An example of such a dependency graph as displayed by Temanejo is shown in figure 2.

It is important to generate and show the dependency graph while the program is running ("online") rather than just collecting the dependency information for later review ("offline"). Firstly the tasks are generated dynamically during runtime hence sometimes the solution to a problem lies in the order in which tasks are generated. Secondly viewing the graph after running the parallel program makes the graph simply the result of a program rather than a tool to debug it. Therefore, passing information during runtime from the program to the debugger is essential. For SMPSs and OMPSs, this is achieved by linking to the library AYUDAME.

2.3. Controlling Task execution

The second requirement for debugging is for the programmer to be able to interact with the running application. This means that the programmer can block a task, stop the program execution at some point, prioritise a task and attach a gdb session to the application. How these features are achieved by Temanejo, is described in the following.

2.3.1. Blocking single tasks

In order to block a specific task, the threads have to be kept from scheduling it for execution. At the same time it must be possible to unblock a task again. We achieve this by building a "to-be-blocked" list in the runtime from the user input to Temanejo. Whenever a thread wants to execute a task, it checks whether the task is in that list and if so he skips it and searches the queues for another one.

2.3.2. Stop Execution when reaching a task

Stopping the program execution at a certain point means to avoid the dequeueing of tasks for any thread. This is implemented by a global flag which is checked by an idling thread *before* looking for a new task in the queues. If the flag is set, the thread is sent back to idle.

2.3.3. Prioritising tasks

In order to prioritise a task, we make use of SPMSs' "critical" queue which is also accessible by adding the keyword highpriority to the pragma line before the function definition. With a right-click on the node in Temanejo the user can prioritise and deprioritise any task before it queued. At the present stage it is not possible to "requeue" a task, i.e. to take a task from one queue and put it into another. In future versions this will be possible which will enable the user to prioritise a task which is already queued in order to execute a specific task as early as possible.

2.3.4. Attaching qdb

TEMANEJO is equipped with the possibility of launching gdb at any point of the debugging session. By default the terminal user interface of gdb starts and lets the user debug any part of the application in the usual line based way.

Another way to launch gdb is by specifying a function in Temanejo at which gdb should set a breakpoint. Again, a gdb process is attached to the application process, a breakpoint is set at the specified function and the program execution is continued, i.e. the control is given back to Temanejo. When the program execution reaches the function, gdb takes control and the user can debug the function with gdb.

2.4. Task duration analysis

In order to enable the StarSs framework to balance each thread's load, the task must neither be to small nor too big. For SMPSs the optimal duration of a task in order to keep all threads busy while avoiding too much overhead wasted in generating, queueing, scheduling and cleaning up tasks, was shown to be of the order of hundreds of milliseconds. An application with tasks which run less than $\approx 100 \mu s$ will suffer a huge overhead in the sense that the master thread will be busy managing the tasks while the worker threads will spend most of their time waiting for tasks. On the other hand, when some tasks are to large, the application runs into a load balancing problem because the worker thread with the large task will again keep other worker threads waiting.

Therefore, it is important for the programmer to know how long the tasks last. In Temanejo the task durations can be shown in colour code for finished tasks. As the communication with the debugger alters the collection of time information, this can only be a rough guide and does not replace a profiling tool. Nevertheless, the ability of displaying timing data in the dependency graph effortlessly proved to be a powerful tool for programmers.

3. Summary and outlook

We presented Temanejo, a debugger for task parallel applications. The StarSs implementations SMPSs and OMPSs in conjunction with the library Ayudame enables the programmer to write task parallel codes and debug them with Temanejo.

TEMANEJO is in constant development process but already provides powerful features which help to debug and enhance task parallel applications. Foremost it shows the dependency graph while it is built up and processed during the runtime of the application. The node colour, the node margin colour, the node shape and the edge colour are four properties which can assigned to display one of the following information: the function which the task executes, the thread which executes the task, the status of the task, the duration of each task (all of the before mentioned for node properties) and the dependency address (for the edge colour).

The presented version Temanejo 0.5 already is a strong tool for the programmer to debug applications parallelised with SMPSs and OMPSs. Nevertheless, many features are desirable in order to make the debugging even more convenient.

In future versions, we will implement more possibilities to analyse the dependency graph. Interesting information about the graph are longest and shortest paths, prioritisation recommendations based on this information, and displaying (or greying out) subgraphs. This will give the developer deeper insights into dependency graphs which become quickly very complex in real-life applications.

Furthermore, we will enhance the control of the application giving better access to queues. This will make it possible to block, prioritise or even run tasks at any time. With the intelligent automatised use of these features it will also be possible to run tasks in a predefined order, e.g. in order of generation, the same order of a previous run or any arbitrary order defined in a configuration file.

Another important tool will be to change the number of threads at any time of the program execution. By that it will be possible to serialise the application at any point and get back to parallel execution afterwards.

Also, we plan to enable the user to launch any debugger instead of just gdb. Finally, we point out that Temanejo is, in spite of its stable operation and richness of feature, still in the process of active development. We encourage the reader to use it and send feedback of any kind in order to enhance this powerful and unique debugger in the most useful way.

Acknowledgements

This work was supported by the European Community's Seventh Framework Programme [FP7-INFRASTRUCTURES-2010-2] project TEXT under grant agreement number 261580. The authors would like to thank Dr. C. Glass for his valuable help to enhance this article.

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